Civil Jet Aircraft Design

Lloyd R. Jenkinson
Senior Lecturer, Loughborough University, UK

Paul Simpkin
Formerly Head of Aircraft Performance, Rolls Royce, UK

Darren Rhodes
Civil Aviation Authority – NATS Department of Operational Research and Analysis (DORA), UK

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This book is dedicated
to our nearest and dearest:
Marie, Dot, Ken and Marjorie

Preface

Excellence in design is one of the principal factors that enable a developed nation to stay competitive in a global economy. The ability of companies to 'add value' to a product or manufactured goods is highly regarded throughout the world. Within this context, aircraft manufacture and operation is regarded as a desirable commercial activity. Many countries who previously were not involved in aeronautics are now moving into the business. However, as aircraft are made technically more complex, involve increasing interdependence between component parts (airframe, engines and systems), and become more multi-national due to the large initial development costs, there is an increasing challenge to the industry. The aircraft design team is in the forefront of this challenge.

Set against this scenario are the conflicts between the various objectives and requirements for new aircraft projects. The designer is concerned about increasing performance and quality, meeting production deadlines, promoting total-life product support, and satisfying customer and infrastructure requirements. Above all these aspects the designer is expected to meet established safety and environmental requirements and to anticipate the sociological and political impact of the design. Balancing all these aspects within an acceptable cost and timescales is what makes aircraft design such a professionally challenging and ultimately satisfying activity.

One of the educational objectives of an aeronautical engineering curriculum is to introduce students to the procedures and practices of aircraft design as a means of illustrating the often conflicting requirements mentioned above. This textbook describes the initial project stages of civil transport aircraft design as an example of such practices. Obviously, the methods used have had to be simplified from industrial practice in order to match the knowledge, ability and timescales available to students. However, this simplification is made in the level of specialisation and detail design and not in the fundamental principles. An example of this approach is the substitution of general purpose spreadsheet methods in place of the specialist procedural-based mainframe programs commonly used for aircraft analysis in industry.

Apart from a general introduction to aircraft project design, this book provides an extension to the classical 'Flight Mechanics' courses. It also bridges the gap between specialist lectures in aerodynamics, propulsion, structures and systems, and aircraft project coursework. The scope of the book has purposely been limited to meet the objectives of undergraduate study. In order to illustrate the basic principles, a simplified approach has had to be made. Where appropriate, reference is made to other texts for more detailed study. Some prior knowledge of conventional theories in aerodynamics, propulsion, structures and control is necessary but where possible the analysis presented in the book can be used without further study. The terminology and the significance of various parameters is explained at the point of application and the main notation listed at the end of the book.

The book is arranged in two parts. In Chapters 1–14 each of the significant influences on aircraft project design is described. This part starts with a broad introduction to civil air transport, followed by a detailed description of the design process and a description of aircraft layout procedures. The next set of chapters are concerned with detailed descriptions of the design methods and an introduction to the principal aircraft components. The concluding chapters deal with the parametric methods used to refine the design configuration and a description of the formal presentation of the baseline design.

The second part of the book (Chapters 15–19) includes an introduction to the use of spreadsheet methods in aircraft design work and four separate design studies. The studies illustrate the application of such spreadsheet methods. Each study deals with a separate design topic. The first shows how a simple design specification is taken through the complete design process. As a contrast the second study deals with non-passenger aircraft design, considering a transport aircraft. As both the previous studies deal with conventional configurations the third study shows how to assess unorthodox layouts. Finally, the last design study shows how you may use the methods to analyse topics other than pure aircraft technical aspects.

No book alone will provide the key to good design. You can only achieve this through the acquisition of knowledge, hard methodical work, broad experience on many different aircraft projects and an open and creative mind. However, we hope that this book will eliminate some of the minor stumbling blocks that young engineers find annoying, confusing and time-wasting at the start of their design work.

Wherever possible System International (SI) units have been used. However, in aeronautics several parameters continue to be used and quoted in non-SI units (for example altitude is normally in feet). It is therefore necessary to have an understanding of different systems of units. To allow conversion between different systems of units a conversion table offers help to both aspiring young designers and older engineers who struggle to convert their past experience into the new system of units.

Finally, it is impossible to make the book complete. The contents and data do not cover all the aspects of civil transport design required by every user. For example, we have not included anything on supersonic aircraft because it is still uncertain if we can solve the environmental problems (noise and emissions) associated with high and fast operations. By the same token we have not gone too far on the inclusion of advanced technologies and materials. Such developments will not affect the main design process and you could allow for them in future studies by establishing factors for use in the standard formulae (e.g. mass and drag reduction factors).

However, allowing for these omissions, we have made a genuine attempt to produce a book that is a starting point for students who want to know more about the fascinating process of commercial turbofan aircraft design.

Acknowledgements

In writing this book we have received a great deal of assistance from many individuals, institutions and companies who have given information, effort and encouragement to us.

We are indebted to the Department of Aeronautical and Automotive Engineering and Transport Studies at Loughborough University who freely supported the preparation and development of the book. We express our thanks to the heads of department, Stan Stevens and Jim McGuirk, and all the members of the aeronautical staff. We are particularly grateful to secretaries Ann French and Mary Bateman for their fortitude in tackling the typing of the original manuscript.

Of all the companies who have provided help and information for this book we would like to thank Rolls Royce PLC and specifically John Hawkins of the advanced projects office, Bruce Astride and members of the aircraft project group.

We also recognise the assistance of Patrick Farmar with respect to the case studies and Bob Caves for his help with various operational issues.

Accompanying data

In association with this book is a series of data sets which are located on the publisher's web site (**www.arnoldpublishers.com/aerodata**). There are five separate sets of data:

- Data A contains technical information on over 70 civil jet aircraft.
- Data B contains details of over 40 turbofan engines.
- Data C includes geographical and site data for around 600 airports.
- Data D defines the International Standard Atmosphere (ISA) and various operational speeds.
- Data E includes definitions and conversions between different parameters and systems of units used in aeronautics.

Students will find the information in these data sets useful in conducting project design studies. Reference to these sets is made at the appropriate points throughout the book and particularly in the chapters concerned with the case studies.

Contents

1

Introduction

On the third of May 1952 a De Havilland Comet 1 aircraft (Fig. 1.1) took off to inaugurate the world's first scheduled jet airline service. This flight from London to Johannesburg was celebrated close to the fiftieth anniversary of the Wright brothers' historic first powered passenger-carrying flight and only 11 years after the first flight of the Whittle jet engine. In the 40-plus years since the Comet flight, jet aircraft have established a dominant position in the civil air transport market and continue to show steady increase in numbers as demand for business, leisure and private flying continues to grow.

Since the end of the Second World War annual air transport passenger numbers have risen from about 18 million to over a billion in recent years. This growth is expected to continue as more nations become industrialised and the world's population becomes more air-minded. This demand for air travel establishes a

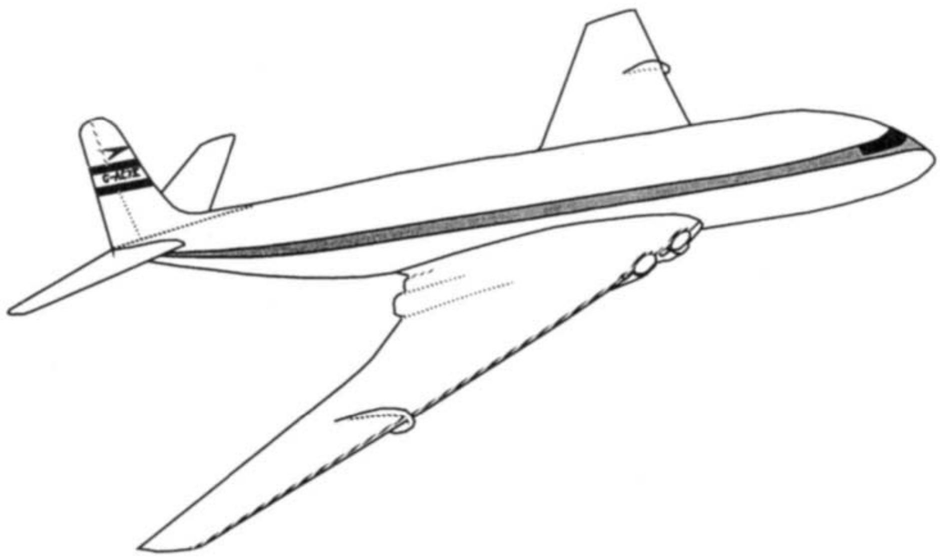

Fig. 1.1 De Havilland Comet 1.

requirement for more aircraft and a larger network of routes. Commercial opportunities arise for both aircraft manufacturers and airlines to meet the expected market.

Estimating traffic growth

To plan aircraft development programmes it is necessary to estimate future trends in air transport for both passenger and freight businesses. The number of aircraft movements is mainly related to the demand for passenger travel. Econometric analysis of historical data shows a strong correlation between world economic growth and the demand for air transport. This confirms that an expansion in business travel and cargo transport are linked to growth in commercial and world trading activity. The level of personal disposable income affects the demand for leisure travel. The standard of service provided has a direct influence on the customer's motivation to travel. All these issues are affected by such factors as the price of the air ticket, international currency exchange rates, availability and frequency of the service, expansion and development of routes and changes in the regulations governing airline operations.

World economic growth is measured by national and global gross national products (GNP). Although the expansion in air transport generally follows the variation in GNP, it has consistently shown a much larger growth rate. In the period 1960–1990 world GNP increased at an average annual rate of 3.8% in real terms whereas airline scheduled passenger traffic (measured in revenue passenger miles, RPM) increased at an annual rate of 9.5%. Over this period the rate of growth of both GNP and RPM have progressively decreased. In the last decade the average world GNP rose by only 2.4% and RPM by 5.7% per year. Even at this lower rate air travel doubles in a 12-year period. These high growth rates have resulted in congestion at the busiest airports and in the most frequently used flight corridors.

Apart from the capital required to purchase new aircraft to meet the demand, large investments are necessary in airports and the associated infra-structure to provide the service. The resultant expansion at existing airports (increased length and number of runways and new terminal facilities) attracts environmental objections and inevitable political interference with the economic model. These factors are difficult to predict and could have considerable effect on the natural expansion of traffic at the busiest city centre airports. Technological developments in air transport management and aircraft design may be the only way that more serious environmental and political restrictions can be overcome.

Factors outside the control of the air transport industry have been shown to affect the national growth in traffic. Sudden changes in fuel price by cartel trading was the cause of depression in demand for air travel in the mid to late 70s. Political unrest, (e.g. terrorism, or in extreme cases war) have always depressed air travel. In the future, the market for air transport may be affected by the expansion of new communication and information technology systems (e.g. tele-conferencing and the internet). This may either depress travel by reducing the need for business trips, or stimulate the market by generating more trade and a stronger demand for

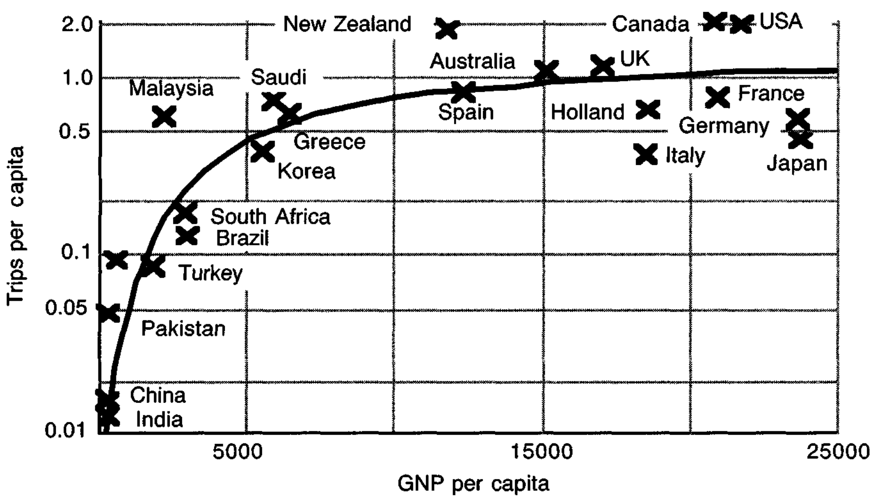

Fig. 1.2 Demand for air travel (source IMF).

holiday travel. Such influences make forecasts based on historical analysis very suspect but the consistency of demand for air travel over the past 30 years gives reassurance that the effects tend to be self balancing.

The influence of national GNP values, and the resulting personal disposable income associated with this, is clearly illustrated by plotting the number of trips per capita against national GNP. The distribution is shown in Fig. 1.2.

In developed countries the air transport market is regarded as mature with growth at about 3–4% per year. The latent demand for air travel is seen in the developing and under-developed industrial countries. The developing countries have air transport growth rates about double that of the developed countries. The poorer countries need the stimulation of industrialisation to provide growth in air transport. This is shown clearly in the potential for growth in China and in the countries of the original USSR.

The UK Office of Science and Technology in a 'Technology Forecast' in 1995 identified three main influences on the growth of air travel:

- gross domestic product (GDP)
- airfares
- propensity to travel

GDP is the dominant parameter and as such needs to be carefully considered in any forecast. The current value of 3% may be varied by ±0.9% in a best and worst case scenario. Air fares have historically reduced due largely to competitive trading and economies of scale but the future is somewhat confused as airline bankruptcies and amalgamations reduce the number of operators. Fares are also affected by the cost of fuel which may vary in the future due to changes in production rates and the addition of environmental taxes (e.g. carbon tax). All these effects need to be reflected in the methods used for forecasting.

The economic modelling of demand for air transport is based on the following two models.

$$(PK) = a \cdot (GDP)^b \cdot (PR)^c \qquad (FTK) = d \cdot (EX)^e \cdot (FR)^f$$

where:

(PK) = passenger–kilometres (FTK) = freight tonne–kilometres
(GDP) = gross domestic product (EX) = world exports
(PR) = passenger revenue per unit (PK) (FR) = freight revenue per unit (FTK)

Historical analysis provides values for the coefficients a, b, c, d, e, f. As passenger demand increases airlines can respond by scheduling extra flights, by using larger aircraft, or by increasing passenger load factors. The linking of passenger–kilometres to aircraft–kilometres involves estimates of passenger load factor (i.e. the ratio of the number of seats filled to the total available) and aircraft size. The following relationships apply:

aircraft–kilometres = (passenger–kilometres)/(passenger load factor)

where: passenger load factor = (passenger–kilometres)/(seat–kilometres) and

aircraft size = (seat–kilometres)/(aircraft–kilometres)

The historical trends in passenger load factor and aircraft size are shown in Fig. 1.3.

It can be seen that since the early 80s both aircraft size and passenger load factor have increased only modestly. This effect may have resulted from the introduction of several new medium-sized aircraft into the market at this time and the expansion of airlines due to deregulation. As a result, the number of city pairs linked by scheduled services nearly doubled in this period. These factors are likely to continue into the near future but may be curtailed by restrictions in air movement growth at some airports due to congestion.

Overcoming the operational problems at airports during busy times of the day has been cited as the main reason to develop new larger aircraft to meet future traffic growth. Larger aircraft would allow more passengers to be moved from

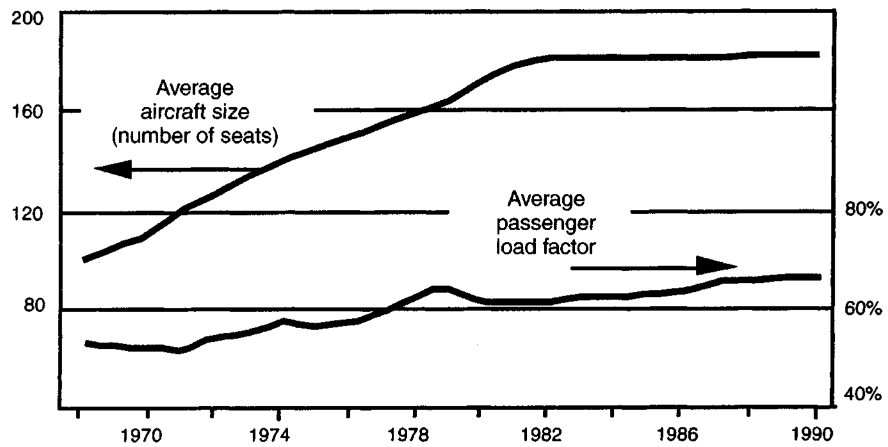

Fig. 1.3 Trend in aircraft size and passenger load factor (source ICAO).

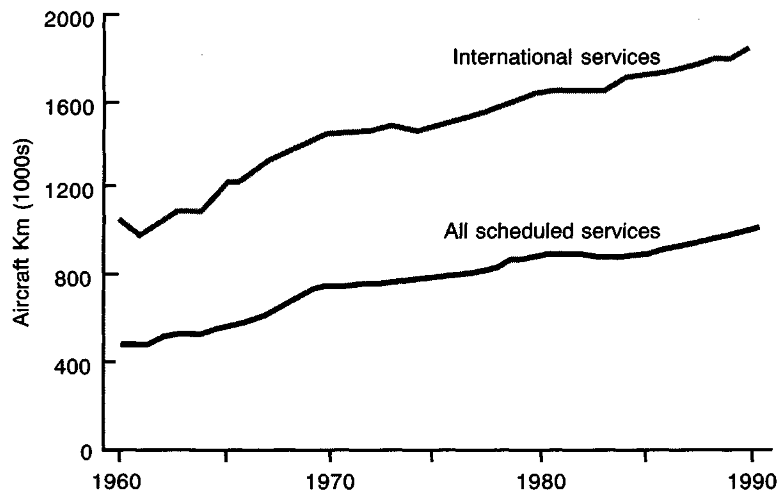

Fig. 1.4 Historical trend in average aircraft stage length (source ICAO).

existing runways and in the airspace near the airport. An estimate by the International Civil Aviation Organisation (ICAO) made in 1992 predicted average aircraft size to rise from 183 seats in 1990 to 220 in 2001.

Airport planning demands a knowledge of the number of aircraft departures. Aircraft stage length links aircraft departures to aircraft–kilometres:

$$\text{aircraft departures} = (\text{aircraft–km})/(\text{stage length})$$

where: stage length = (aircraft–km)/(aircraft departures).

The historical trend in average stage length is shown in Fig. 1.4.

In the past 20 years the growth in average stage length has been between 1 and 2% per annum. The figure above shows that the largest growth has been in the long-haul routes. This has been made possible mainly by the increased range capability of new aircraft types and the development of new markets, particularly in the Pacific region. This trend is expected to continue and result in annual growth of 1% in average stage length.

Forecasting growth can be achieved by considering the average annual rates of change in each of the main variables:

$$\%\,(\text{aircraft–km}) = \%\,(\text{passenger–km}) - \%\,(\text{load factor}) - \%\,(\text{average size})$$

$$\%\,(\text{departures}) = \%\,(\text{aircraft–km}) - \%\,(\text{stage length})$$

ICAO made the following predictions in 1992 (Table 1.1).

The world's commercial activity associated with aerospace is huge (amounting to over $100B in the mid-90s). This is shared almost equally between companies specialising in airframes, engines, airframe systems, airport systems and airport facility.

There are currently about 350 000 civil aircraft registered in the world but most of these are in the light/personal aircraft category. Only 50 000 are registered in the civil commercial category (hire and reward), and only about 10 000 of these are

Table 1.1 Historical traffic data (source ICAO)

	1970	1980	1990	2000	Average annual growth rate (%) 70–80	80–90	90–00
Passenger-km (billions)	382	929	1654	2830	9.3	5.9	5.0
Passenger load factor (%)	52	61	66	68	1.6	0.8	0.3
Passenger aircraft size (seats)	109	171	183	220	4.6	0.7	1.7
Aircraft stage length (km)	738	875	983	1100	1.7	1.2	1.0
Aircraft-km (millions)	7004	9350	14 307	19 800	2.9	4.3	3.0
Aircraft departures (thousands)	9486	10 691	14 553	18 000	1.2	3.1	2.0

The table above includes all-freight movements but excludes operations of aircraft registered in the Russian Federation.

turbofan airliners. Although civil turbo-powered airliners represent a small percentage of the total aircraft population they account for 75% of the total value of all aircraft. The dominance of turbofan-powered aircraft is illustrated by the historical trend of commercial aircraft by type as shown in Fig. 1.5. In the early days most scheduled flights were made by piston engined aircraft but as the turbojet and later the turbofan engines were developed these dominated the market and superseded the piston types. At the present time few new piston-powered

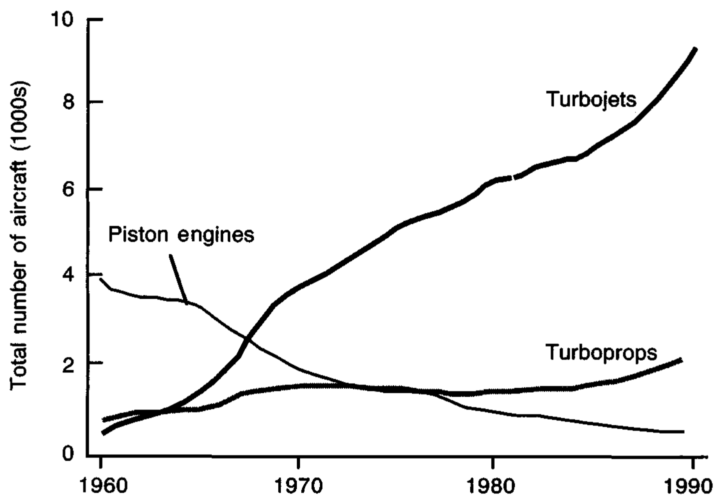

Fig. 1.5 Historical trend in world fleet mix (source ICAO).

Table 1.2 World fleet mix forecast (source UK Department of Trade)

Category	Current fleet	Forecast deliveries	Deliveries value ($B)	% of total
Turbofan airliners	9680	12 100	725	75
Turboprop airliners	5000	3900	50	5
Business jets	8000	7200	75	8
Business turboprops	9500	6000	30	3
Turbine helicopters	12 000	9000	80	8
Light aircraft	300 000	20 000	3	<1
Civil aircraft (total)	344 180	58 200	963	100%

aircraft are used by airlines. For the short-haul market the fuel efficiency of the turboprop aircraft still attracts operators.

The current and projected fleet of civil aircraft together with the projected cost data for new aircraft, up to 2015, are shown in Table 1.2.

The projected traffic growth over the next 20 years (Fig. 1.6) averages 5% per year but this figure is not expected to be constant across all regions. For developed airline networks (mostly North America and Europe) the growth is predicted to be 4%, whereas for the Asia/Pacific Ring area a faster growth of 7% is expected. The projected figures do not include the potential for air travel from undeveloped economic areas like China, Russia and Africa. The projected growth forecasts could be greatly under-estimated if these areas develop faster than expected.

The demand for air travel is affected by the cost of air fares which over the past 30 years have progressively reduced in real terms. On this basis the transAtlantic return ticket is currently only about 40% of the fare charged in 1960. This reduction has been achieved by the development of a strong market with several

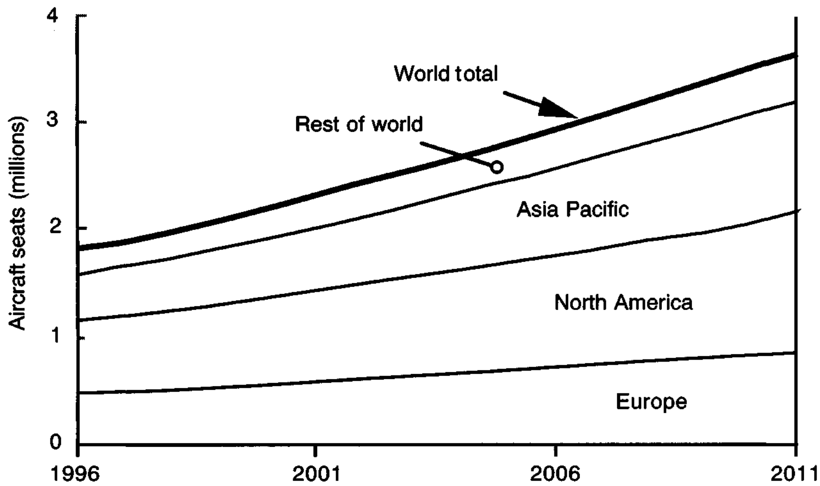

Fig. 1.6 Average annual growth rates (source Airbus).

airlines competing for business. Over the past few years this fierce competition has resulted in reduced revenue and poor commercial returns for some airlines. If a more commercially sensible trading environment is adopted in the future this may result in more expensive airfares which in turn will reduce demand and therefore the potential revenue. This dilemma illustrates the precarious nature of airline business.

Modal choice

The travelling public has available a wide choice of modes of transport including car, bus, train, ship and aircraft. By far the most significant advantage of air travel is the time saved by the fast cruising speed. Professor Bouladon of the Geneva Institute aptly described this in his analysis of transport gaps in 1967.

The total trip time shown in Fig. 1.7 is a combination of delay caused by the infrequency of the service, the speed of travel and the wasted time due to the interconnection of services.

With only minor alterations his hypothesis remains valid today. Of the three 'gaps' identified, the short- and long-haul ones are directly targeted by the air transport industry. Reducing each of the component times contributing to the overall trip time presents opportunities for both operational and technical improvements in new air transport and continues to challenge aircraft designers, airline managers and airport operators. For short stages it is no longer acceptable to have long reporting times prior to boarding. The most successful local air services attempt to copy bus and train operations in which tickets are bought at the boarding gate at the time of embarking. For longer journeys the pre-loading of luggage and cabin supplies means that earlier reporting is necessary.

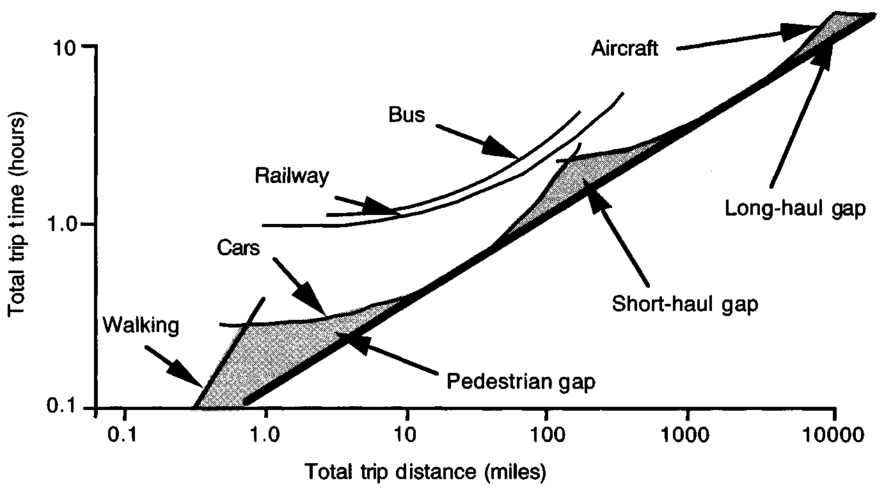

Fig. 1.7 Transport gaps (source Bouladon).

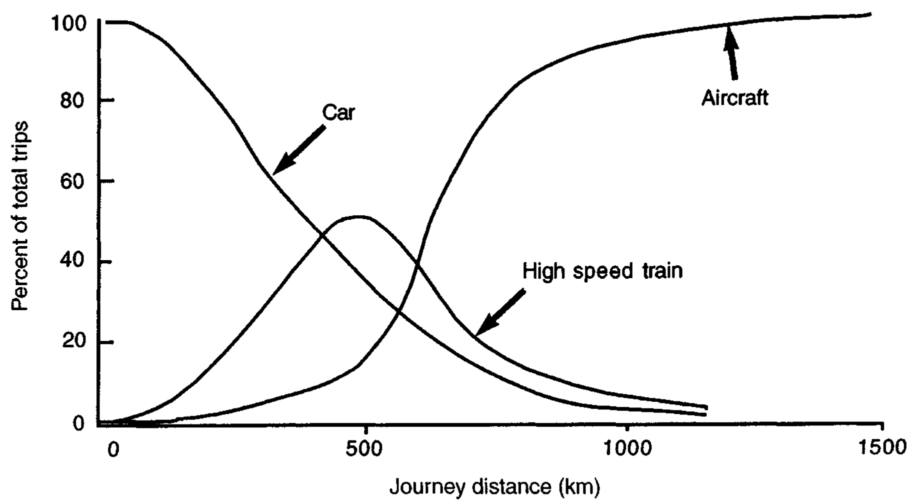

Fig. 1.8 Modal traffic split (source Airbus).

The influence of time saving is shown by the modal split (for business travel) between the three major transport forms of travel (Fig. 1.8).

As we all know, for shorter journeys and where a suitable public transport system is not available the private car is the natural choice of travel. For journeys less than 400 km/250 miles the car is the dominant mode of transport. In this market the train and bus are seen to be disadvantaged by the infrequency of service, by the out-of-pocket cost and the slow journey times (especially for distances greater than 250 km/150 miles. As public transport services are developed into a frequent, fast and comfortable option (e.g. by the introduction of high speed trains), the competition to air becomes stronger in the mid-range, (250–600 km/150–350 miles). Over about 600 km/350 miles the time saving of air travel becomes attractive and air dominates the market. As shown by Bouladon, the total journey time is affected by delays and transfers between modes. The links to the airport (road, rail and public services) is a major influence on the success of the service. For leisure travel the choice of mode is strongly influenced by ticket price and airport convenience. This has led to the development of the non-scheduled/charter air transport sector. As personal disposable income increases and more holiday resorts are developed this sector will become increasingly significant.

The aircraft market

Traffic growth and modal split are the major factors in the demand for new aircraft but these are not the only parameters. Aircraft have only a finite life and this means that there is a considerable market for replacements. It is estimated that only about 60% of the total new aircraft will be required to meet the expected increase in traffic. The rest will be needed to replace existing aircraft which have reached the end of their useful life. Some of the replacement aircraft will be introduced because of environmental and regulatory changes (e.g. older types not meeting local noise regulations) and others will be needed to replace aircraft which are less efficient and more costly to operate than new types.

The number of aircraft required is also affected by the trend to larger aircraft, longer-range non-stop flights, and the passenger's preference for the wide-body configuration. In the next 20 years it is estimated that about 13 500 new aircraft will be needed to match the increase in demand for air travel and to replace older types. More than half of these aircraft will be sized at less than 200 seats. This represents between $B950 and $B1500 turnover to cover the purchase of new equipment and the associated after-sales trade. As the economies of the developing countries grow, new manufacturing companies will be attracted to the civil aircraft market opportunities. It is likely that these new companies will be started as new joint ventures with established aircraft manufacturers. The number of competing companies may therefore increase, adding further commercial pressure to the current manufacturing industry.

The market for new aircraft is dominated by very few airlines. About 50% of all turbofan airliners are held by only 18 airlines. The top 100 airlines operate 81% of all jet airliners. This centralisation may change in the future due to trade and traffic liberalisation and the resulting challenges to existing monopolistic business practices.

Although aircraft design deals mainly with the technical/engineering aspects it must be remembered that many non-technical influences are important. It is necessary to understand these influences at the onset of the design so that they can be fully considered and due allowance be given to them in the development of the aircraft specification. For example, analysis of demand for civil aircraft shows how the air transport sector is only one option available to the travelling public. For most journeys a mixture of transport modes is necessary; therefore each mode is not independent. Within this context the availability, cost and efficiency of the road and rail networks to and from an airport are known to be major components in the choice of air travel.

The increase in demand for air travel will lead to more aircraft movements. This will result in higher aircraft utilisation and the requirement for more aircraft to be produced. The operational problems from such developments are now becoming a major concern. Congestion at airports and in the main air routes, environmental damage and the consumption of scarce resources will increasingly be factors to be considered by the designers and operators.

The commercial transport market may be roughly divided into four sections depending on aircraft size and capability (large, wide-bodied, narrow-bodied and regional). The largest aircraft (often referred to as jumbos) are wide-bodied multi-deck configurations of which the Boeing 747 is typical. Passenger capacities exceeding 400 with range capability exceeding 7000 nm and take-off length of about 11 000 ft are typical. With the expected growth in passenger traffic and the shortage of available take-off slots at convenient times there is a renewed interest in expanding the large aircraft sector. Competitors to the B747 will include new super-jumbos (new large aircraft) with passenger capacity between 500 and 700 with a range of 7500 nm.

The next largest sector includes wide-bodied turbofan aircraft which are smaller